<u>In the specification</u>:

Page 2, lines 20 and 22, and page 5, line 10, of the originally filed specification are amended herein as shown. For more convenient review, all six pages of the specification are presented here.

LASER WAVELENGTH TRIPLER WITH HIGH QUANTUM EFFICIENCY

Field of the Invention

This invention relates to frequency conversion of laser light .

Background of the Invention.

In some situations, it is desired to convert the wavelength of a laser beam to one or more higher wavelength values (i.e., introduce a "red shift"), where a coherent light source is needed in a spectral region where a primary source is not available. A red shift may be introduced to minimize optical absorption that would otherwise seriously degrade the intensity of an incident light beam at the lower wavelength, for example, in a nonlinear optical semiconductor crystal. In another situation, introducing a red shift may allow the modified laser beam to hit certain target molecular absorption resonances that are to be studied.

Red shift of laser radiation can be achieved using stimulated Raman scattering (SRS) in gases, liquids or solids, as described by W. Koechner in Solid State Laser Engineering, Springer Verlag, Berlin, New York, 1988, pp. 526-535. In an SRS system, an incident laser beam having a selected frequency $\nu 0$ interacts with a selected material and a light beam having a Stokes-shifted frequency $\nu 0 - \Delta\nu$ issues from the material, where $\Delta\nu$ is a frequency difference that is characteristic of the material. A selected wavelength, $\lambda = 1.064\ \mu m$, of an Nd:YAG laser can be converted, using SRS in a medium such as H_2, which provides a vibrational wavenumber (difference) $\Delta\nu' = 4155\ cm^{-1}$, to a resulting wavelength $\lambda = 1.91\ \mu m$ radiation, for example.

Red shifting of laser radiation can also be implemented using an optical parametric oscillator (OPO) in which the "pump" laser photon decays into two smaller energy photons, referred to as the "signal" and the "idler." An OPO approach creates coherent light that is red shifted with respect to the original "pump" laser photon.

Using these traditional methods for red shifting laser radiation, it is difficult to achieve high conversion efficiency ($\approx$ 100 percent) because of the presence of a quantum defect; the red shifted signal photon carries away less energy than was

present in the original pump photon. This defect may be especially critical when the frequency of the red shifted signal photon is much less than the frequency of the pump photon.

What is needed is a red shift process that provides more than one red shifted photon, all with approximately the same photon energy. Preferably, this approach should be capable of providing two or three signal photons having substantially the same frequency, where the sum of the energies associated with the photons produced is approximately equal to the pump photon energy.

Summary of the Invention

These needs are met by the invention, which provides a cascaded frequency down-conversion in which each pump photon produces more than one red-shifted photon. In one embodiment, passage of a pump photon (3ω) through a selected first nonlinear crystal produces a first parametric conversion $(3\omega \rightarrow 2\omega + \omega)$; and passage of the resulting $2\omega + \omega$ photons through a selected second nonlinear crystal produces a second parametric conversion $(2\omega + \omega \rightarrow \omega + \omega + \omega)$. The first and second nonlinear crystals are aligned within a cavity resonating at frequency 2ω, which is trapped within the cavity until its conversion to $\omega + \omega$ photons that may exit from the cavity. In another embodiment, the first and second parametric conversion processes are $(4\omega \rightarrow 2\omega + 2\omega)$ and $(2\omega \rightarrow [[2]]\omega + \omega)$.

Brief Description of the Drawings

Figures [[1 and 2]] 1, 2, 3 and 4 are schematic views of [[two]] four embodiments of systems for practicing the invention.

Description of Best Modes for the Invention

Figure 1 illustrates a first embodiment of a system 11 for practicing the invention. A pump laser beam of photons, having an arbitrarily selected individual associated energies of $3h\omega$, is produced by a pump laser 13 and is directed toward a resonant cavity 15. The resonant cavity 15 includes a first partly transmitting mirror 21, a second partly transmitting mirror 23, spaced apart from each other by a selected distance D, and a first nonlinear crystal 25 and a second nonlinear crystal 27 that are aligned serially between the first and second mirrors as shown. Ideally, each of the first mirror 21 and the second mirror 23 is substantially fully

transmitting (80-100 percent) at the (angular) frequencies ω and 3ω and is substantially fully reflective (98-100 percent) at the frequency 2ω. Preferably, the first NLC 25 and of the second NLC 27, have anti-reflective coatings that pass substantially all incident light at the frequency 2ω and at the frequencies ω and 3ω.

The first and second nonlinear crystals (NLCs), 25 and 27, have the respective lengths d(1) and d(2) and have the respective refractive indices n(2ω;1) and n(2ω;2) at the frequency 2ω. Ideally, the distance D satisfies a resonance relation

$$\{D + d(1)\cdot(n(2\omega;1) - 1) + d(2)\cdot(n(2\omega;2) - 1)\}\cdot(2\omega/c) = N2\cdot\pi, \quad (1)$$

where N2 is a selected positive integer. Optionally, the mirrors 21 and 23 are contiguous with ends of the respective NLCs 25 and 27 so that D = d(1) + d(2).

The embodiment illustrated in Figure 1 relies upon optical parametric oscillation (OPO), which is discussed by A. Yariv in Optical Electronics in Modern Communications, Oxford Univ. Press, New York, 1997, pp. 308-322, and in W. Koechner op cit, pp. 519-526. An assembly of pump laser photons with individual energies 3hω is provided by the pump laser 13, is received at and passes through the first mirror 21, and is received at the first NLC 25. The first NLC 25 is configured to convert a pump photon (3ω) to first-converted and second-converted photons (2ω and ω, respectively) according to the conversion

$$3\omega \rightarrow 2\omega + \omega. \quad (2)$$

In practice, a small fraction of the pump photons is not converted on this pass through the first NLC 25 and ultimately passes out of the cavity 15. Substantially all pump photons (3ω) ultimately disappear from within the resonant cavity 15.

The resulting first-converted and second-converted photons (2ω + ω) are received by the second NLC 27, which is configured to convert a first-converted photon (2ω) to two second-converted photons according to the conversion

$$2\omega \rightarrow \omega + \omega. \quad (3)$$

Ideally, a pump photon (3ω) passes through the first and second NLCs, 25 and 27, and is converted to three second-converted photons (ω) according to the cascade conversions

$$3\omega \rightarrow 2\omega + \omega \rightarrow \omega + \omega + \omega. \tag{4}$$

In practice, a fraction f2 of the second-converted photons is not converted on the first pass through the second NLC 27 and moves approximately parallel to the axis AA of the resonant cavity in one or more cycles. Each of the first and second mirrors is substantially fully reflecting at the frequency 2ω so that the only substantial loss mechanism within the cavity 15 is down conversion according to Eq. (3). Ultimately, substantially all first-converted photons (2ω) are converted to two second-converted photons ($\omega + \omega$).

Substantially all pump photons (3ω) are converted to three second-converted photons ($\omega + \omega + \omega$) ,according to the conversions in Eq. (4), and pass out of the cavity 15 through the second mirror 23, which is fully transmissive at the frequency ω. One result of this process is that a single pump photon (3ω) is converted to three second-converted photons ($\omega + \omega + \omega$) having substantially equal energies, with a probability reaching about 50 percent, so that the quantum efficiency of conversion can be greater than 100 percent.

Figure 2 illustrates a second embodiment of a system 31 for practicing the invention, in which the first and second NLCs of Figure 1 are replaced by a monolithic, quasi-phase-matched (QPM), periodic grating structure 34, within a resonant cavity 35 that is defined by two partly transmissive mirrors, 35 and 37. Ideally, each of the first mirror 41 and the second mirror 43 is fully transmissive (80-100 percent) at the frequencies 3ω and ω and is substantially fully reflective (98-100 percent) at the frequency 2ω. The QPM grating structure 34 includes first and second cascaded QPM grating structures, 45 and 47, with selected grating periods $\rho 1$ and $\rho 2$, respectively, which are phase matched and configured to promote the photon conversion reactions in Eqs. (2) and (3), respectively, for the pump beam provided by the pump laser beam source 33. Preferably, the first and second QPM grating structures, 45 and 47, are contiguous, not spaced apart from each other. The photon conversion process indicated in Eq. (4) in the system 31 occurs in a manner similar to the photon conversion process in the system 11 in Figure 1.

The light source, 13 and 33, for the pump laser beam in Figures 1 and 2 may be Nd:glass, Nd:YAG, Nd:$YAlO_3$, Nd:YVO_x, Ho:YLF, Ti:Al_2O_3 or any other suitable intense light source. The first and/or second nonlinear crystal may be $LiNbO_3$, $LiIO_3$, $KTiOPO_4$, $RbTiOAsO_4$, $CsH_yD_{2-y}AsO_4$, β-BaB_2O_4, $Ba_2NaNb_{35}O_{15}$, Ag_2AsS_3, $AgGaS_2$, $AgGaSe_2$, GaAs, $ZnGeP_2$, and any other suitable nonlinear crystal.

In another embodiment of the invention, the pump laser beam source 13 in Figure 1 is (re)configured , as illustrated in Figures 3 and 4, to provide photons with individual energies 4hω, where ω is arbitrarily selected, and these photons are received by the cavity 15. The first NLC 25 is (re)configured to convert pump photons (4ω) to first and second first-converted photons according to the conversion process

$$4\omega \rightarrow 2\omega + 2\omega. \qquad (5)$$

Each of the two resulting first-converted photons 2ω is received by the second NLC 27, which is (re)configured to convert a first-converted photon (2ω) to two second-converted photons according to the conversion process

$$2\omega \rightarrow \omega + \omega. \qquad (6)$$

That is, one or both of the first and second first-converted photons (2ω) provided by the first NLC 25 undergoes the conversion indicated in Eq. (6). The original pump photon (4ω) is thereby converted to three or four resulting photons (ω) according to the cascade conversion process

$$4\omega \rightarrow 2\omega + 2\omega \rightarrow \omega + \omega + \omega + \omega. \qquad (7)$$

Most practical cascade conversion schemes will involve, as part of the process, two consecutive conversion steps that proceed according to Eq. (4) or according to Eq. (7). The first and/or second nonlinear crystal, 25 and/or 27, may be chosen from the same group of nonlinear materials as set forth above, namely $LiNbO_3$, $LiIO_3$, $KTiOPO_4$, $RbTiOAsO_4$, $CsH_yD_{2-y}AsO_4$, β-BaB_2O_4, $Ba_2NaNb_{35}O_{15}$, Ag_2AsS_3, $AgGaS_2$, $AgGaSe_2$, GaAs, $ZnGeP_2$, and any other suitable nonlinear crystal.

Ideally in this embodiment, each of the first mirror 21 and the second mirror 23 is substantially fully transmitting (80-100 percent) at the (angular) frequencies ω and 4ω and is substantially fully reflective (98-100 percent) at the frequency 2ω.

Preferably, the first NLC 25 and the second NLC 27, have anti-reflective coatings that pass substantially all incident light at the frequency 2ω and at the frequencies ω and 4ω. Preferably, the cavity length D again satisfies the resonance relation in Eq. (1).

This cascade conversion approach may also be used for the system 31 shown in Figure 2, in which the first and second NLCs of Figure 1 are replaced by a monolithic, quasi-phase-matched (QPM), periodic grating structure 34, within a resonant cavity 35 that is defined by two partly transmissive mirrors, 45 and 47.